Vol. 7, No. 2, pp. 17-22, December 2008

INTERNATIONAL JOURNAL OF SAFETY
www.kosos.or.kr

Nondestructive Contactless Sensing of Concrete Structures using Air-coupled Sensors

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(Received July 5, 2008; Accepted December 15, 2008)

Abstract : Recent developments in contactless, air-coupled sensing of seismic and ultrasonic waves in concrete structures are presented. Contactless sensing allows for rapid, efficient and consistent data collection over a large volume of material. Two inspection applications are discussed: air-coupled impact-echo scanning of concrete structures using seismically generated waves, and air-coupled imaging of internal damages in concrete using ultrasonic tomography. The first application aims to locate and characterize shallow delamination defects within concrete bridge decks. Impact-echo method is applied to scan defected concrete slabs using air coupled sensors. Next, efforts to apply air-coupled ultrasonic tomography to concrete damage imaging are discussed. Preliminary results are presented for air-coupled ultrasonic tomography applied to solid elements to locate internal defects. The results demonstrate that, with continued development, air-coupled ultrasonic tomography may provide improved evaluation of unseen material defects within structures.

Key words: nondestructive evaluation, concrete, imaging, impact echo, ultrasonic, tomography

1. Introduction

Most nondestructive evaluation (NDE) techniques require good contact between the sensor and tested concrete surface to obtain reliable data. But the surface preparation is often very time and labor consuming due to the rough surface or limited access of concrete structures. One approach to speed up the data collection process is to eliminate the need for physical contact between the sensor and tested structure. For this purpose, air-coupled ultrasonic sensing techniques have been developed by a research group in the University of Illinois at Urbana-Champaign for NDE of concrete structures [1]. Basic idea behind the air-coupled sensing techniques is very simple. That is, when an impact or any other wave sources are applied on concrete surface, part of the generated wave energy leaks into surrounding air due to large acoustic impedance mismatch between air and concrete. These leaky waves can be captured using high-sensitivity acoustic wave sensors and are processed for further applications.

On the other hand, visual images that describe the location, size and shape of embedded damage or flaws in concrete structures provide a direct way to help engineers evaluate the condition of the structures. Many methods based on mechanical wave, infrared, electromagnetic wave, to name a few, have been developed for nondestructive imaging of concrete structures. Among them, mechanical wave based imaging techniques such as impact-echo scanning and ultrasonic transmission tomography have been widely used as an cost effective technique for concrete structures [2,3].

In this paper, two imaging applications for NDE of concrete structures are discussed. Those are (1) air-coupled impact-echo scanning of concrete structures using seismically generated waves, and (2) air-coupled imaging of internal damages in concrete using ultrasonic tomography. The first application aims to locate and characterize shallow delamination defects within concrete bridge decks. Impact-echo method is applied to scan defected concrete slabs using air coupled sensors. Next, efforts to apply air-coupled ultrasonic tomography to concrete damage imaging are discussed.

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2. Theoretical Basis

2.1 Impact-echo method

Impact-echo (IE) method was first developed at the National Institute of Standards and Technology in 1980s, and then further developed at Cornell University under the direction of Mary Sansalone. Here principle of the IE method is briefly described [4]. Referring to Figure 1, a transient stress pulse is introduced into a test object by an impact force applied on the surface of structure. The generated transient waves are reflected by internal interfaces or external boundaries. The surface displacement is measured by a receiving sensor and analyzed in the frequency domain. The distance to the reflecting interface h is related to the P wave velocity C_p and the peak frequency f by

$$h = \beta \frac{C_p}{2f}$$

where β is a factor related to section shape. According to the standard test method, for plates, $\beta = 0.96$. As shown in the equation, the distance to the reflection interface such as delamination can be estimated by measuring the peak frequency and the P wave velocity of the tested structures.

In this paper, impact-echo method is used to scan concrete slabs. Peak frequency of each scanning point on the test slab is extracted and re-arranged for imaging of concrete slab.

2.2 Ultrasonic Tomography

Tomography is a process of reconstructing a cross-sectional image using ray projection measurements through the section [5]. The tomography method measures time-of-flight of ultrasonic waves along different wave paths through the material as shown in figure 2. Variation in internal material properties affects the travel time of ultrasonic waves along each path. In classical solutions the reconstruction can be performed by a two-dimensional convolution or a matrix inversion, however, these solutions require specific source-receiver geometries and assume straight ray paths [6]. These geometry restrictions can rarely be met when imaging solid objects, and the high contrast in material acoustic velocities lead to nonlinear ray paths. Iterative methods are often used for tomography of solids to accommodate different geometries and accurately model curved ray paths [5]. The program 3DTOM developed by Jackson and Tweetony [6] models nonlinear ray paths in iterative solver and is often used for concrete tomography.

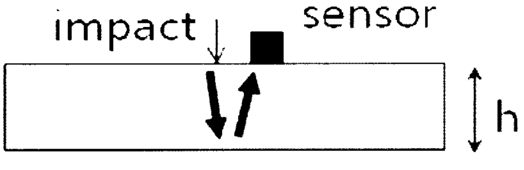


Fig. 1. Impact-Echo Method

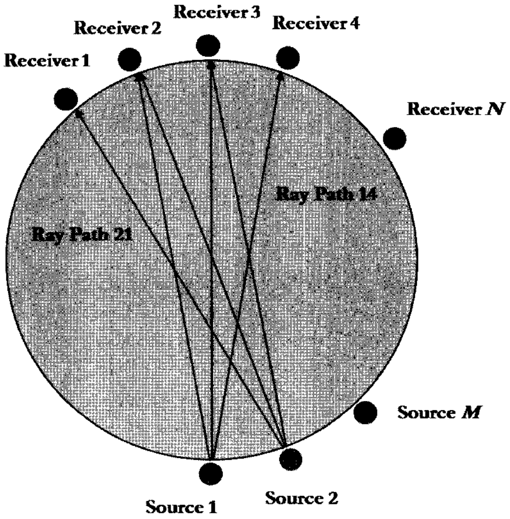


Fig. 2. Ultrasonic Tomography

In this study, 3DTOM which combines the data measured at different angles through the section is used to reconstruct the section image.

3. Air-coupled Imapact-Echo Imaging

3.1 Concrete Slab Specimen and Air-coupled Sensor

Air-coupled impact-echo tests were carried out on a manufactured concrete test slab. This slab simulates a typical bridge deck in the state of Illinois USA, with a total thickness of eight inches and steel cover depth of approximately two inches. The slab contains pre-placed defects. Corrosion-induced delamination defect is simulated by placing a double layer of thin polymer sheets on top of the steel bar mesh indicated with a red circle in figure 3.

Several commercially-available air-coupled sensors have been investigated for the purpose of detecting seismic signals in concrete. All of the sensor types are able to detect impact-echo and seismic responses from concrete in a fully contactless manner. Of these, the conventional vocal microphone provides the lowest sensitivity and frequency bandwidth as shown in figure 4. However, this sensor is still able to collect impact echo and seismic data without any external bias or

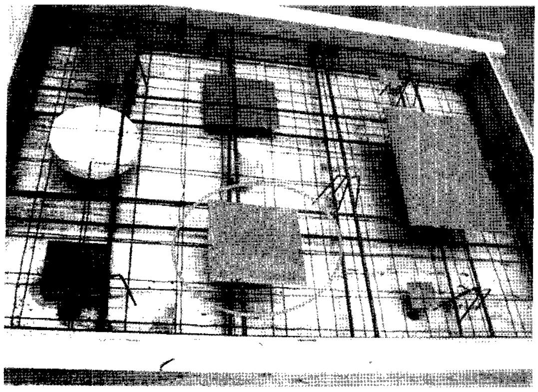
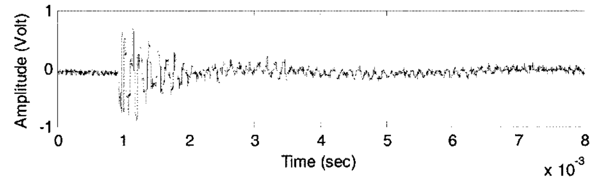


Fig. 3. Concrete Slab Specimen and Simulated Defects Positions

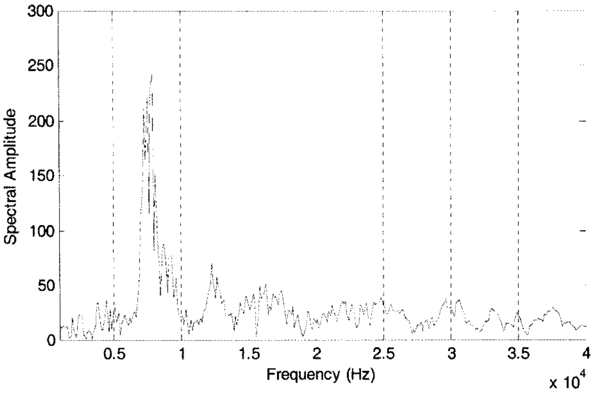
noise shielding, and allows close placement of the sensor to the surface. Thus the conventional vocal microphone (SHURE SM58) was selected for implementation in the tests.

3.2 Experimental Results

Air coupled impact echo data were collected at 2.5 cm spacing in a grid around the area above a 300mm × 400mm top delamination defect (referring to figure 3). The frequency domain data are represented in area scan image. Area scan image of frequency data collected over the whole delamination area is shown in figure 5. The boundaries of the defect are indicated with blue lines. Clear indications of high amplitude in the frequency contour plot are seen when the tests are located above the defect. This frequency (around 2.58 kHz) matches very well with first harmonic of the flexural vibration of the defect which was predicted by finite element analysis. Thus, we conclude that the proposed air-coupled impact echo testing configuration is sensitive enough to capture meaningful data from defects, since the extent of delaminated area is indicated by high amplitude at a certain frequency component. This sort of data presentation offers an effective manner to indicate the location and extent of delamination in an image.



(a) Time Domain



(b) Frequency Domain

Fig. 4. Impact-Echo Signals Measured by SHURE SM-58

4. Air-coupled Tomographic Imaging

4.1 Test Specimens

A set of specimens were fabricated to test the air-coupled tomographic imaging. Polyvinyl Chloride (PVC) was selected for the first specimens because its attenuation is somewhat lower than that of concrete and is absorptive rather than scattering. This leads to clearer transmitted signals for the initial trials. Three cylindrical phantoms six inches (15 mm) in diameter were prepared with various inclusions, as shown in figure 6.

4.2 Air-coupled Transducers

For this work an air-coupled ultrasonic testing system was developed using time averaging and pulse compression of a frequency modulated signal. Two SENSCOMP 600 capacitive micro-machined ultrasonic transducers (CMUTs) having matching layers were used to send and receive the signals. CMUTs provide a better transmission into air than conventional piezoelectric transducers. These sensors each had a central frequency of

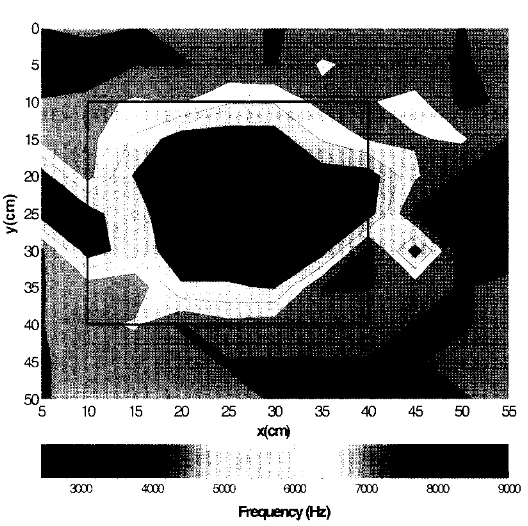


Fig. 5. Impact-echo Scan Image Collected over Area of 300mm×400mm Delamination

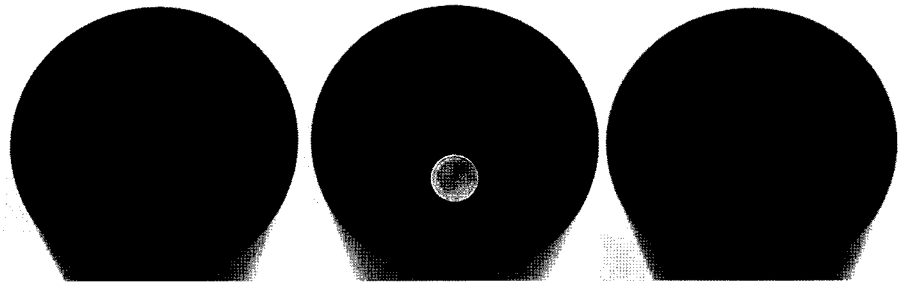


Fig. 6. PVC Phantoms

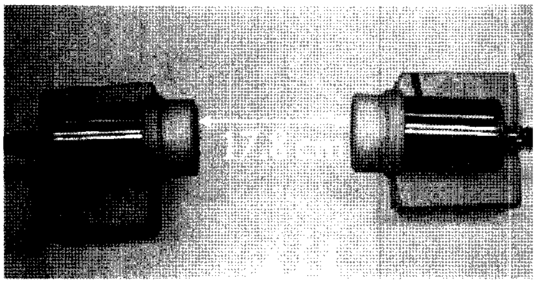


Fig. 7. Reference Signal Test Setup with Two Air-coupled Sensor (SENSCOMP 600)

55 kHz. The applied chirp ranged from 75-40 kHz and had a time-bandwidth product of 40. This provides a signal-to-noise ratio improvement of 16 dB in pulse compression. Each signal was collected over 4000 time averages and then cross-correlated with a reference signal through air only as shown in figure 7.

As seen in figure 8, a sharp peak in the resulting signal corresponds to the arrival time of the pulse. By subtracting the time of flight in the reference signal, the arrival time through solid and air is calculated.

4.3 Tests and Results

Measurements were made through each specimen by direct transmission (180° transducer spacing) and at a 40° offset with an air gap of 1.2 inches (30 mm). The specimen was rotated in 10° increments to collect a total of 54 projection measurements. Because of the high velocity contrast between the air and solid, it can be assumed that the path of the first arriving wave is direct from the transducer to the nearest point on the cylinder. The time of flight through the air gap was subtracted from the total time so that the sources and receivers could be represented on the surface of the cylinder in the reconstruction model. A field of 24x24 pixels was used for the model. 3DTOM program is used for reconstruction. The known velocity of PVC was used as the initial guess for the velocity field. The final images were interpolated bi-linearly for display and interpretation. The results of the tomographic reconstructions are shown in figure 9. In each of the images the actual shape and location of the inclusion is indicated by a white line. Generally the reconstructions capture the shape and location of each of the inclusions. Some additional high and low velocity regions appear as artifacts of the reconstruction. These artifacts could be reduced, and the contrast and resolution improved if a greater number of ray measurements were made. The steel bar appears as a low velocity inclusion because of

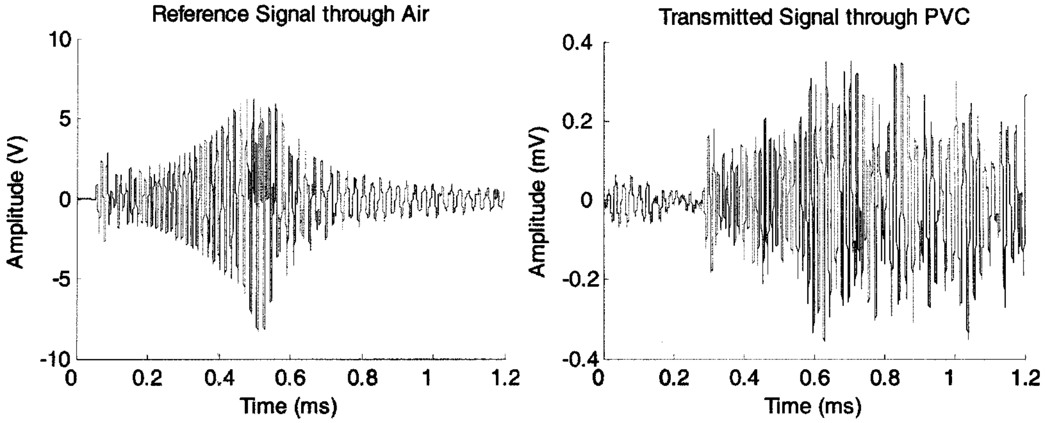


Fig. 8. Collected Signals: Reference Signal through Air (left) and Transmitted Signal through PVC (right)

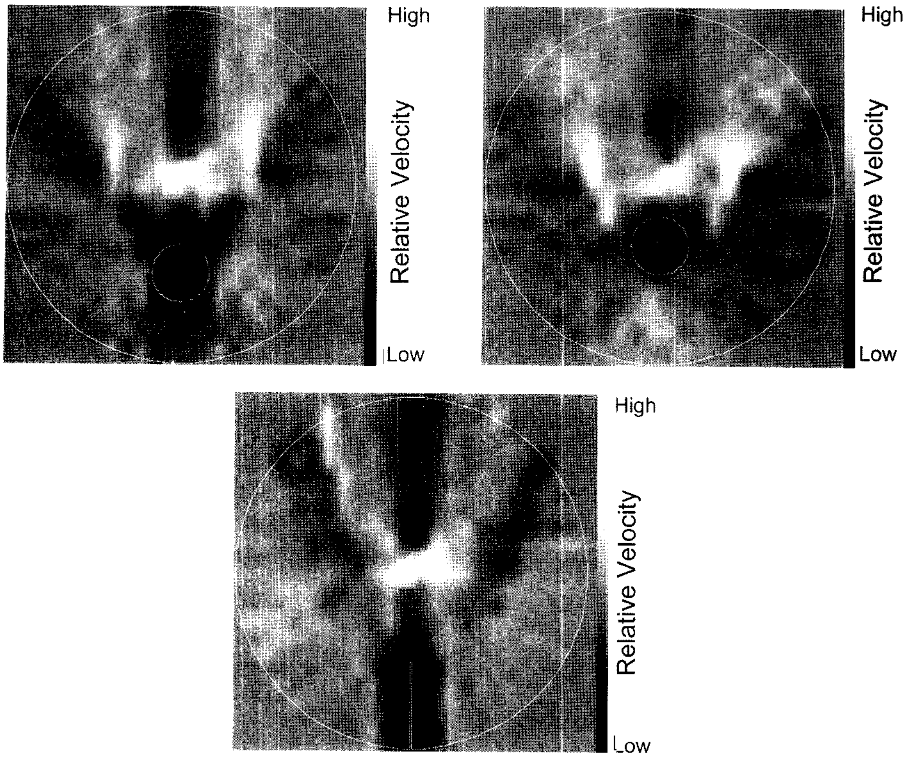


Fig. 9. Tomographic Images of the Three PVC specimens. Upper left is the void. Upper right is the steel bar. Lower is the crack.

a problem in the signal processing. The wave that bypasses the bar is greater in amplitude than the wave transmitted through the bar; because the difference in their arrival times is less than 1/2 of the wavelength, the signal through the steel is eliminated by the signal processing as unwanted noise. The use of a higher frequency might eliminate this problem, but would limit the depth of penetration possible through concrete.

Preliminary tests have also been performed on one of the concrete specimens. Geometries and inclusions of the concrete specimens are nearly identical to the PVC specimens. The measurements of transmission through concrete cylinders have been less successful. There is no clear trend in the variation of the travel times through concrete. Although no attenuation tomographs have been computed so far, it was decided to also compare the amplitudes of the transmitted signals. There is a strong trend in the amplitude of the transmission through the PVC specimen with lower amplitudes when the wave passes near the void. The amplitudes of the signals transmitted through concrete show a similar trend, although the magnitude of the differences is lower and the variation is much higher.

5. Conclusions

Air-coupled impact-echo tests with impactors and conventional microphones are possible. Flexural vibration modes of the delamination can be used to characterize and image defects in an effective manner. Fully air-coupled ultrasonic measurements were successfully obtained through three 6" (150 mm) PVC specimens. The reconstructed tomographic images indicate the shape and location of inclusions. Further development is necessary to detect high velocity inclusions and demonstrate possible resolution improvements. Measurements through concrete were less successful, although some indication of the void is given by the attenuation measurements.

Acknowledgements

This work is supported by grants from the United States National Science Foundation under grant number CMMI 0710777 (Dr. Lawrence C. Bank program manager), and the NCHRP-IDEA program under grant number 134 (Dr. Inam Jawed program manager).

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